Energy Resources Beyond Earth – SSP from ISRU

Gateway to Space
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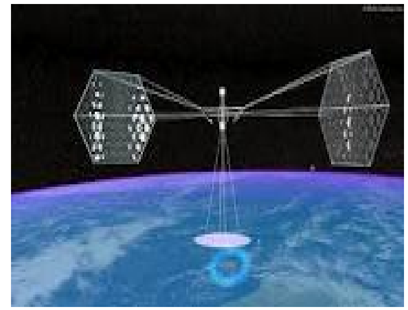
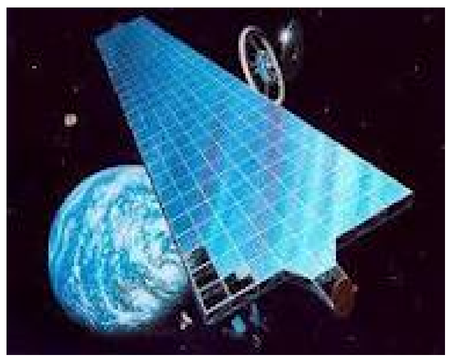
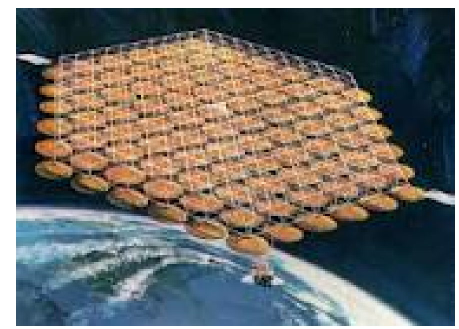
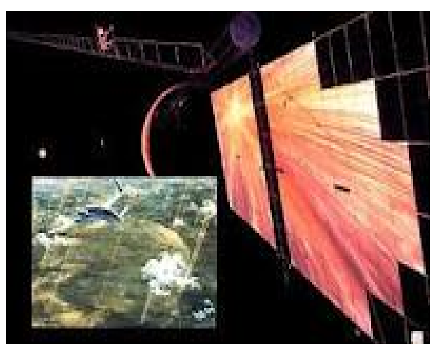
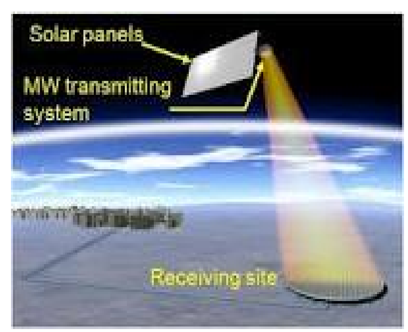
Various Architectures for SSP

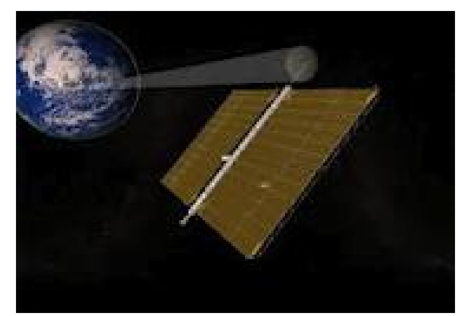






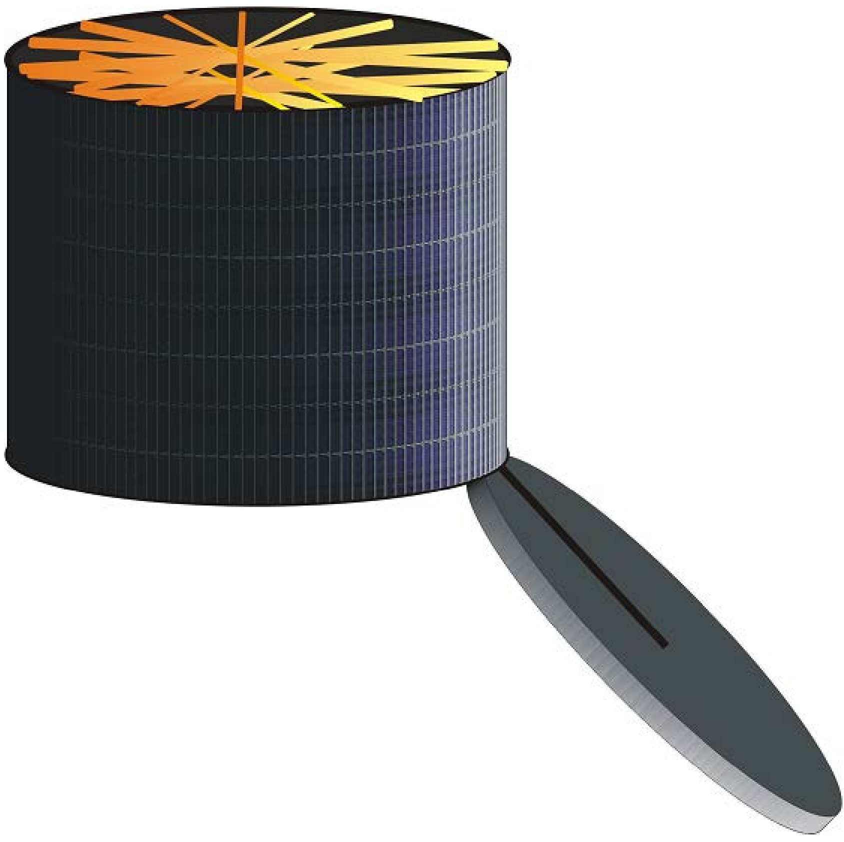






Benefits of “Tin Can” SPS

- No moving parts
- Shadowed side rejects heat
  – Heat pipes cool sunlit side
- Good structural integrity
- Interior free of solar wind
- Constant, baseload power
- Negligible station-keeping (after spin-up)



1 drawback – lots of solar panels required

SSP from Lunar Materials

- The Moon is 21% silicon
  - 7% aluminum - for metal contacts
- Lunar escape velocity = 2.4 km/s
  - For Earth v_e=11.8 km/s
  - Remember that K.E. = ½ mv^2 *(24X)*
- Abundant solar power (70%+ at poles)
- Ultra-high vacuum (10^{-11} Torr)
- Luna has everything needed for SSP!

Extract Raw Materials

PATENTS

3 May 11	7,935,176	OXYGEN EXTRACTION APPARATUS AND PROCESS
9 Dec 08	7,462,820	ISOTOPE SEPARATION PROCESS AND APPARATUS THEREFOR
16 Aug 05	6.930,304	PROCESS AND APPARATUS FOR ISOTOPE SEPARATION IN A LOW-GRAVITY ENVIRONMENT
2 Sept 04	6,614,018	PROCESS AND APARATUS FOR CONTINUOUS-FEED ALL-ISOTOPE SEPARATION IN MICROGRAVITY USING SOLAR POWER

PAPERS

"Oxygen Extraction from Lunar Regolith via Free-Fall Induction Heating," Meno, Schubert, Intl Space Development Conf. 19-22 May, 2010, Huntsville, AL

"Large Thoria Castings for Ultra-high Temperature Processing with Oxygen," Schubert, Williams, Wilks, Ende, Babcock, Meno, USACA 34th Annual Conference on Composites, Materials & Structures (ITAR restricted) 23-26 Jan 2012

"Advances in Extraction of Oxygen and Silicon from Lunar Regolith," Schubert, Williams, Bundorf, Di Sciullo Jones, AIAA SPACE 2010, 30 Aug -2 Sept 2010, Anaheim, CA

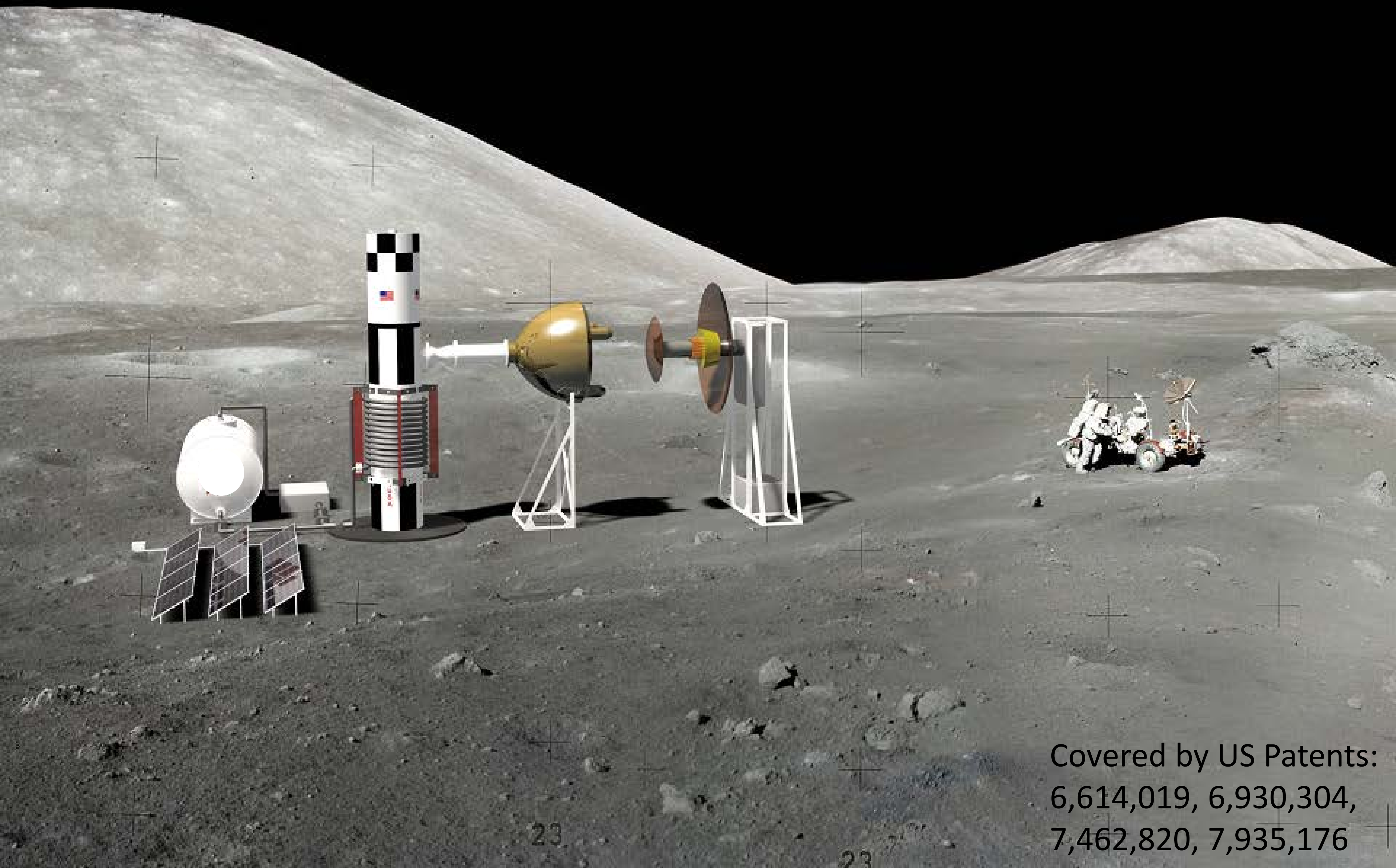
"Survey of Ultra-High Temperature Materials for Applications Above 2000 K," Cunzeman, Schubert, AIAA SPACE 09, 14-17 Sept 2009, Pasadena, CA

"Ultra-High Temperature Materials for Lunar Processing," Schubert, Cunzeman, Am. Soc. of Engineering Educators, Annual Conference, Pittsburgh, PA, June 2008

"A Novel Means for ISRU Oxygen Production," Schubert, Space Resources Roundtable IX, Golden, CO, 25-27 Oct 2007.

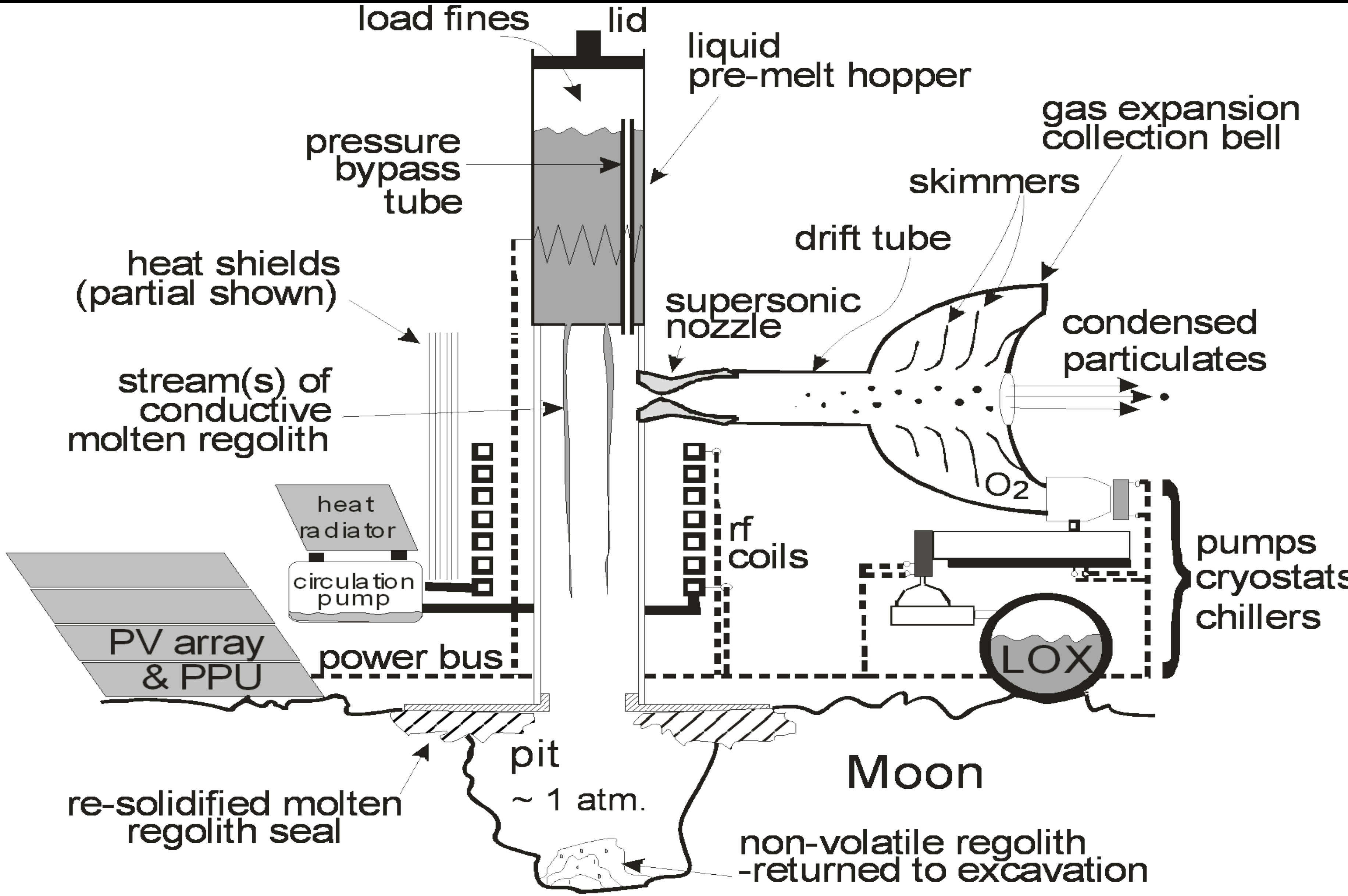
"Oxygen Separation from Lunar Regolith," Schubert, 23rd Int'l Conf. on Environmental Systems, Chicago, 9-12 July 2007

Lunar Factory for LOX and Metals



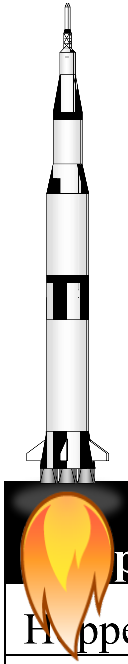
Covered by US Patents:
6,614,019, 6,930,304,
7,462,820, 7,935,176

The Supersonic Dust Roaster

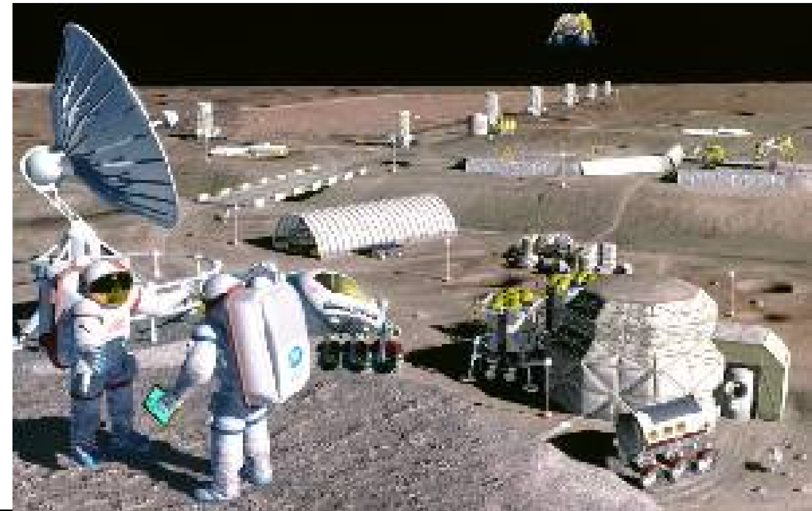


Thorium Oxide for 2950 K

- Largest thoria pieces ever reported.
- Built on NASA SBIR Phase II
- Withstands molten regolith

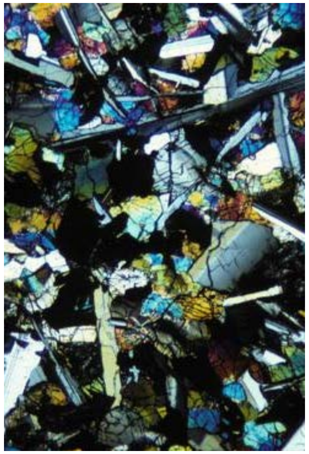


Performance



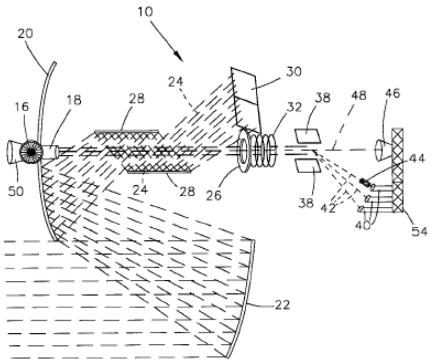
Component	Mass (kg)	Power (kw)	Key Assumptions
Hopper	257	49.8	50 stream apertures, 45 minute heat-up time
Free-fall shaft	143	19	Conditions based on temperature, length calculated by matching flow rate to evaporation
SS nozzle	44.8	0	Area relation to determine shape
Drift tube	9.69	0	1.8 m long, shares same area as the exit of the nozzle.
Expansion bell	1.28	0	Half sphere, tube area 5% of total exit area so we capture 95% flow.
Pumps and cryochillers	62	2.16	Mass of pumps is linearly related to the flow rate.
Passive cooling pipes	260	0	Length for radiative cooling from 1200 down to 200 K
Storage	100	0	Mass of large storage tank (buried)
Subtotal	876	**70.9**	12x12m solar panels
Grand Total	**1302**		Assumes 6 kg/kw, including power processing unit

Metals Extraction (Si, Al, Fe)



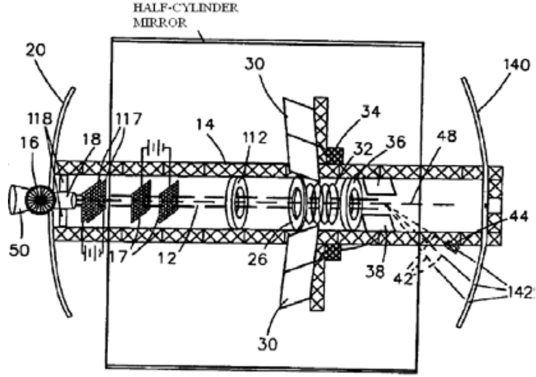
- Isotope Separator downstream of Dust Roaster:
  - Ballista are ionized
  - Expanding plasma gated by slits
  - Transverse electric field separates by the charge/mass ratio of isotopes
  - Collect species
  - Accrete slag

$$a = \left(\frac{q}{m}\right) \cdot E$$



US 6,618,014
for zero gravity

US 6,630,304
lunar gravity



Value-Added Products

PAPERS

“Materials Selection and Processing for Lunar Based Space Solar Power,” Schubert, Materials Challenges in Alternative and Renewable Energy, J. Wiley, Hoboken, NJ, 224, v7, 2011“Costs, Organization, and Roadmap for SSP,” Schubert, Online Journal of Space Communications #16, May, 2010

“Dual Use Technologies for Self-Sufficient Settlements: From the Ground Up,” Schubert, Intl Space Development Conf. 19-22 May, 2011, Huntsville, AL

“A Novel Method for Element Beneficiation Applied to Solar Panel Production,” Schubert, Space Exploration 2005, Albuquerque, NM

“Electrical Energy Storage using only Lunar Materials,” Dietzler, Schubert, Space Manufacturing 14: Critical Technologies, 2010

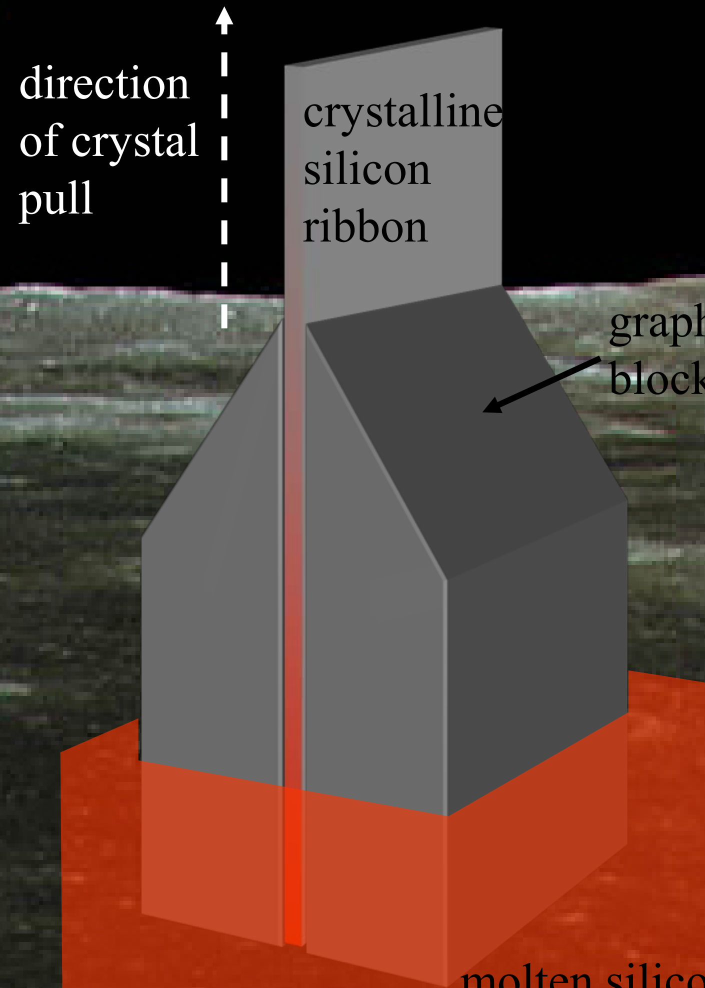
“Solar Panels from Lunar Regolith,” Schubert, Intl Space Development Conf, 28-31 May 2010, Chicago, IL

“Materials Selection and Processing for Lunar based Space Solar Power,” Schubert, Materials Challenges for Energy: 2010, 21-24 Feb, Cocoa Beach, FL

“Harvesting of Lunar Iron: Competitive Hands-on Learning,” Schubert, Beatty, Am. Soc. of Engineering Educators, Annual Conference, Pittsburgh, PA, June 2008

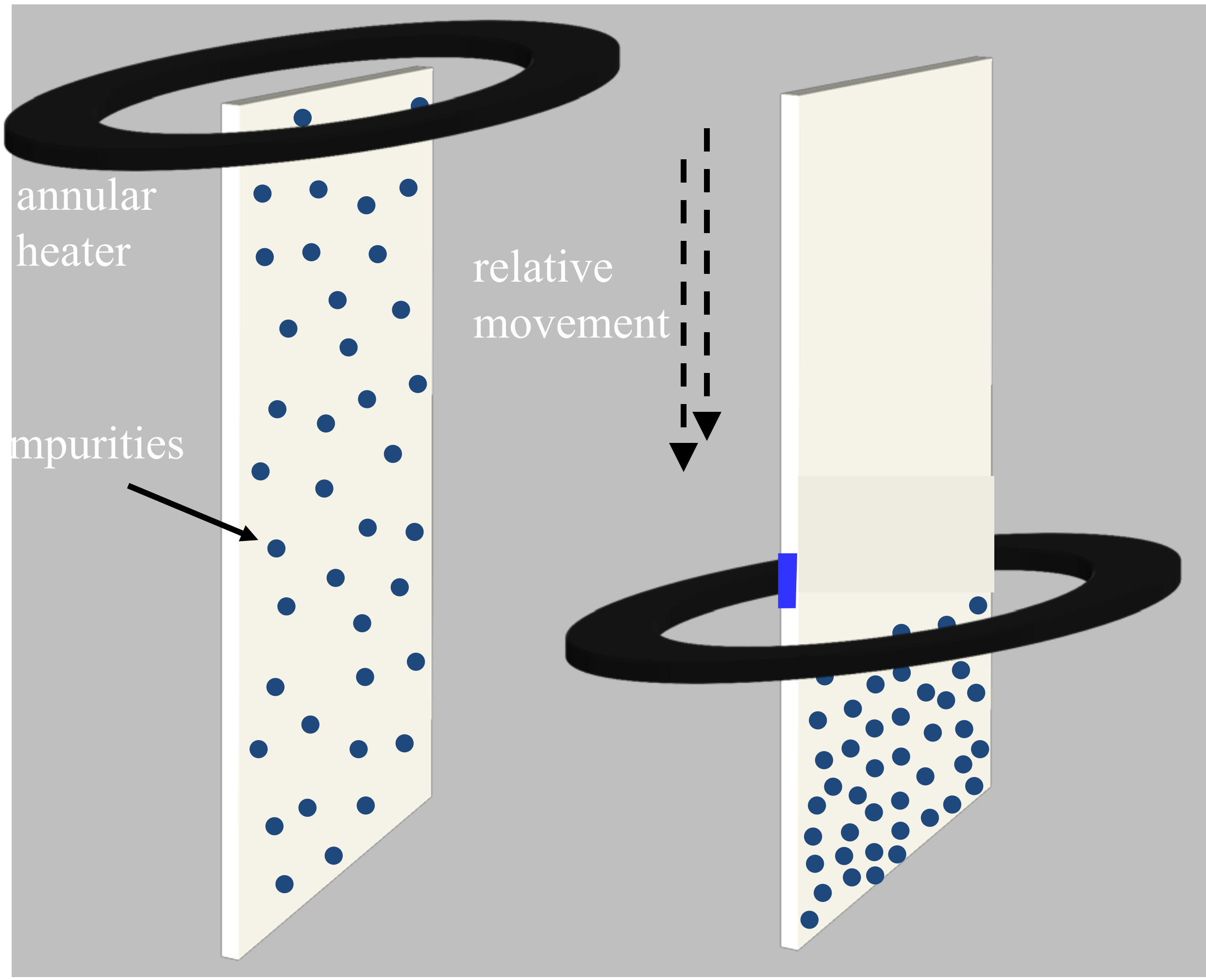
Silicon ribbon formation

- Edge-Fed Growth
- Single crystal possible
- Solar furnace heated
- Form continuous ribbons
- Cut into slabs with:
  - diamond saw
  - laser

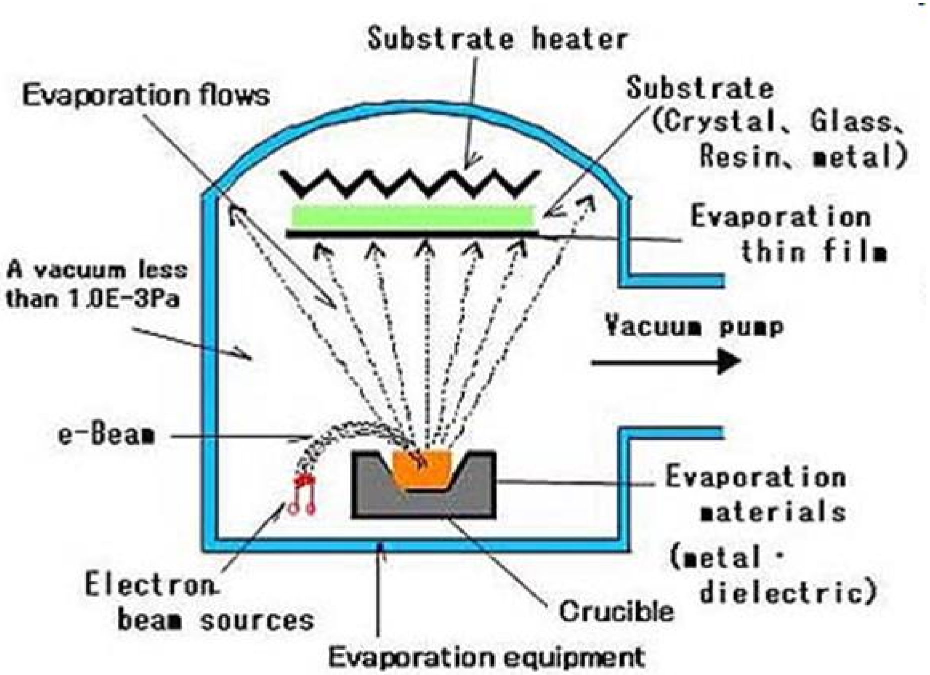


Float-Zone Recrystallization

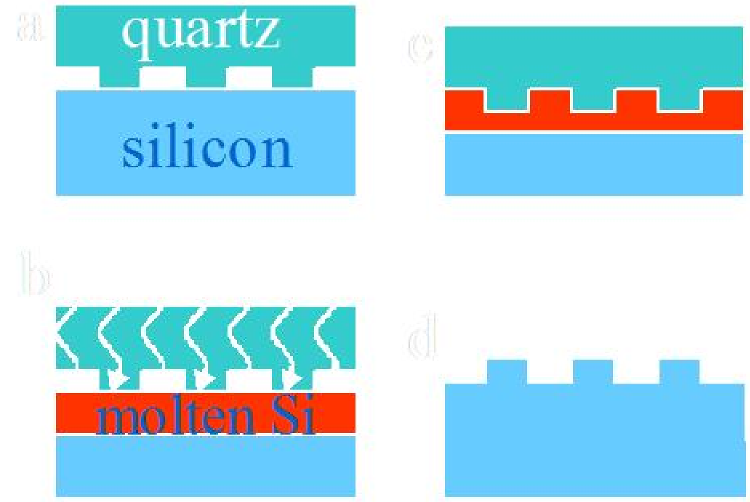
- Segregation
- Seed crystal
- Cut end off
- Single-crystal silicon rectangles



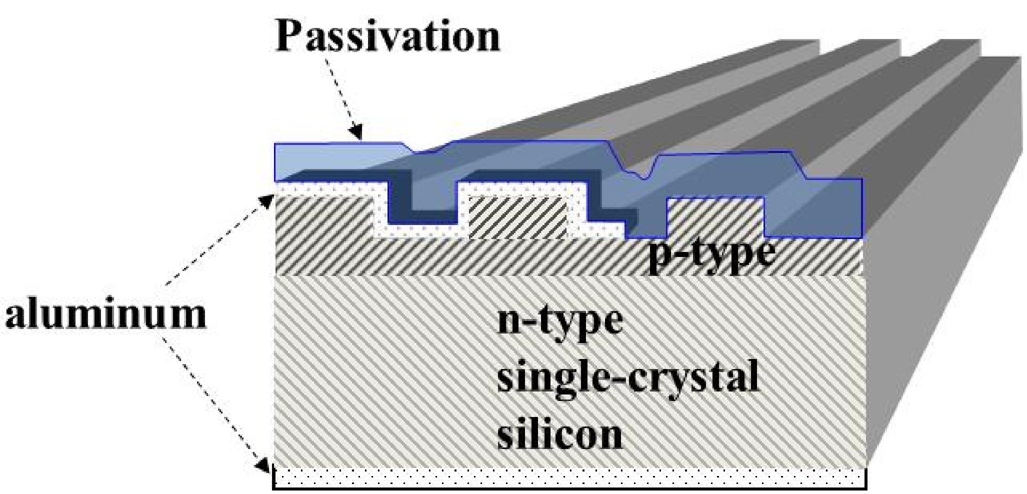
Metallization



Anti-reflection

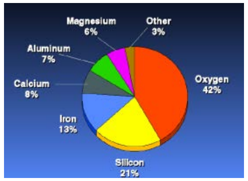


PV panel



Slag from Isotope Separator

- Melting points greater than 3000 °K
- Accrete/form by directional adhesion

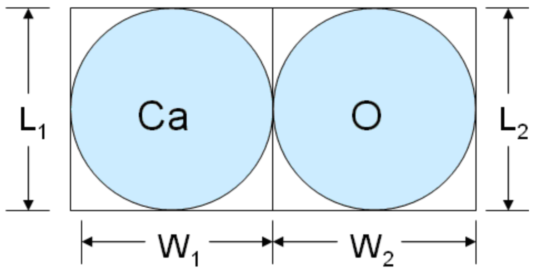


REGOLITH COMPOSITION (per 1000 kg of regolith)

Mineral	Weight %	MP (K)	Density	Volume (m^3)
SiO_2	47.3	1986	2334	0.203
TiO_2	1.6	2116	4230	0.00378
$Al2O_3$	17.8	2327	3970	0.0448
FeO	10.5	1650	6000	0.0175
Na_2O	0.7	1405	2270	0.00308
K_2O	0.6	623	2350	0.00255
MnO	0.1	2113	5370	0.000186
Cr_2O_3	0.2	2603	5220	0.000383
MgO	9.6	3099	3600	0.0267
CaO	11.4	3172	3340	0.0341

SLAG COMPOSITION

Mineral	Weight %
MgO	45.7
CaO	54.3

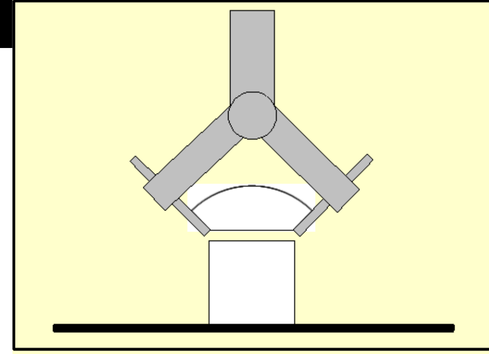


$$Area = (L_1 \times W_2) + (L_2 \times W_2)$$

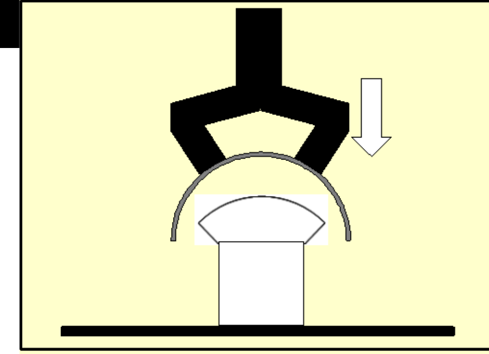
SLAG DENSITY		
Combined Density (kg/m^3)	Void Volume Percentage	Adjusted Density (kg/m^3)
3459	7.4	2573

Loading

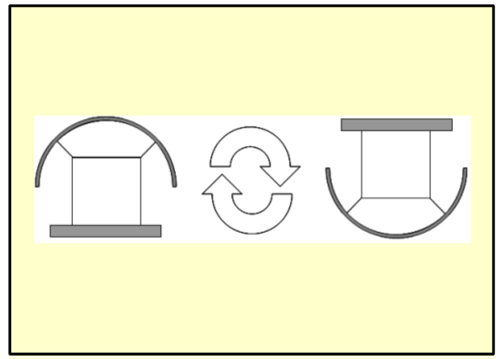
- Steps to automatically load payload canisters
  - Solar panels
  - Slag targets
  - Iron shell



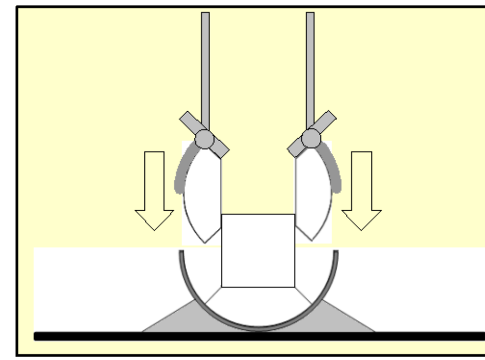
(a) Robotic arm places a slag target on top of a cube-shaped stack of solar panels moving along a conveyor belt.



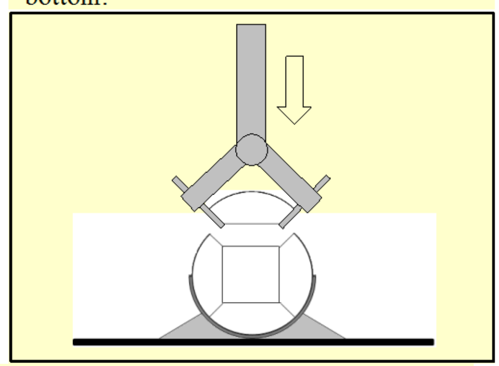
(b) Electromagnetic arm then lowers half of the iron shell on top of the slag and solar panel stack.



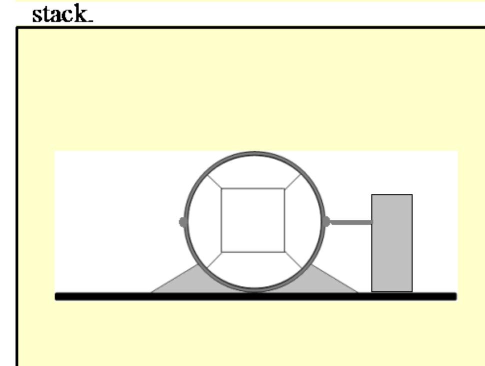
(c) Shell, slag target, and solar panels are rotated 180 degrees so shell is on the bottom.



(d) Robotic arms insert four slag targets, one along each side of the solar panel stack.



(e) Robotic arm places final slag target on top of solar panels.



(g) Electromagnetic arm lowers second half of iron shell into place. After shells are arc-welded shut, container is completely assembled.

Transportation

PATENTS

10 Oct 06	7,118,075	SYSTEM AND METHOD FOR ATTITUDE CONTROL AND STATION KEEPING
7 Feb 06	6,994,296	APPARATUS AND METHOD FOR MANUEVERING OBJECTS IN A LOW/ZERO GRAVITY ENVIRONMENT

PAPERS

“Technical Feasibility of a Novel Method for Station Keeping,” Schubert, Simpson, Lin, AIAA SPACE 09, 14-17 Sept 2009, Pasadena, CA

“System for Electromagnetic Capture of Lunar-launched Payloads into GEO,” Duncan, Schubert, Delaurentis, 43rd AIAA/ASME/SAE/ASEE Joint Propulsion Conference, Cincinnati, OH 8-11 July 2007

$$\sigma_2 = \frac{wR_2}{2t}\cos 2\theta$$

Launch

$$\sigma_1 = \frac{wR_2}{2t}$$

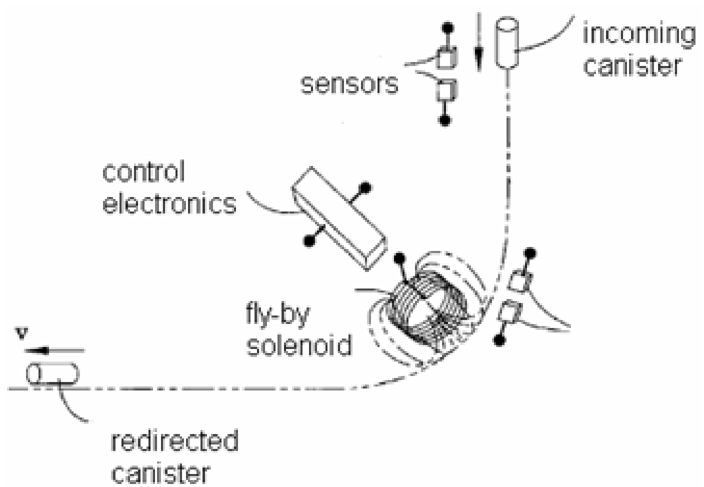
- 80 g acceleration limit (782 m/s^2)
  - stresses at 3% of yield strength
- 3.7 km electromagnetic catapult

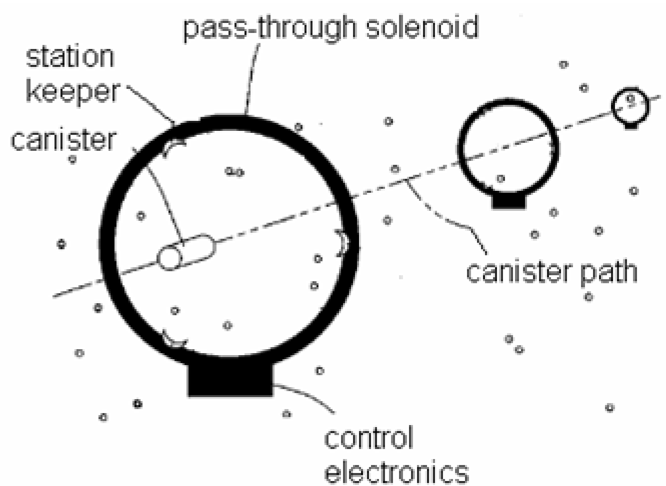
Container Dimensions and Cargo.

Radius Without Shell (m)	0.144	
Radius With Shell (m)		0.151
Total Volume (m^3)		0.0143
Mass of Container (kg)		13.68
Mass of Slag (kg)		25.53
Mass of Panels (kg)		10.80
Total Mass (kg)		50.0
Max Panel Lengths (m)	0.167	
Number of Panels		476
Total Panel Area (m^2)		13.23

Electromagnetic Payload Catcher

- Two means to influence a payload canister:
  - Velocity reduction through a solenoid
    - "Pass-Through"
  - Velocity direction change past a solenoid
    - "Fly-By"





Physics Modeling

- Pass-Through solution driven by amperage

$$F = .5 * \mu_0 * \frac{N^2}{L^2} * I^2 * A_{Pay}$$

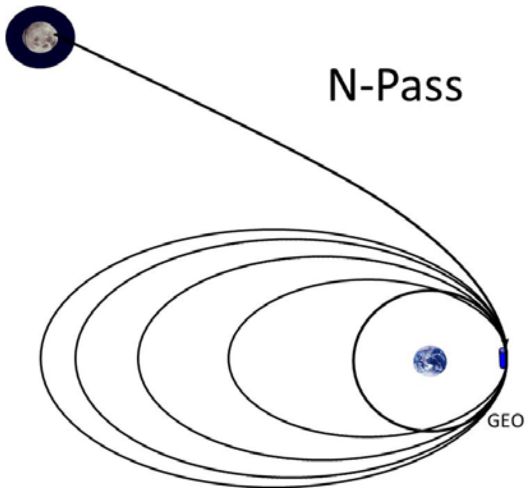
- Fly-By solution driven by proximity

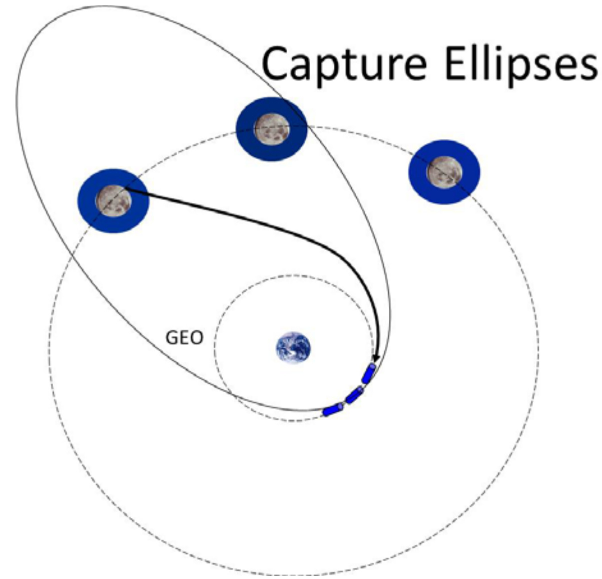
$$F = \frac{M * m_p}{\mu * r^2}$$

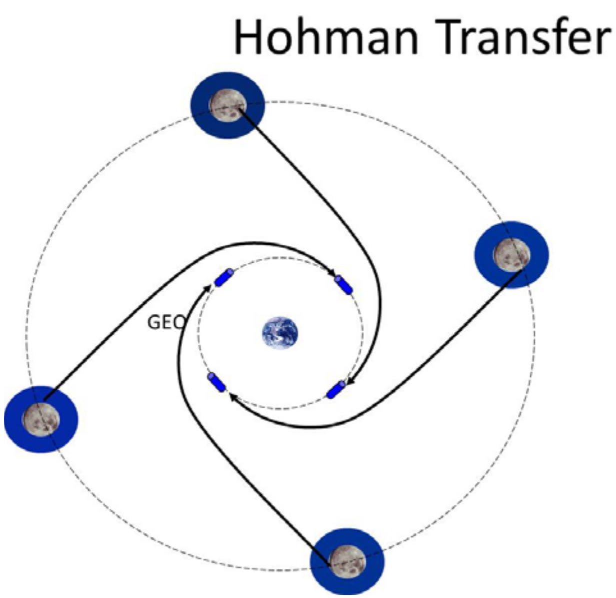
$$M = \pi * a^2 * N * I$$

$$m_p = B * \chi * \mu * \pi * (\frac{d}{2})^2$$

Orbital Mechanics Options





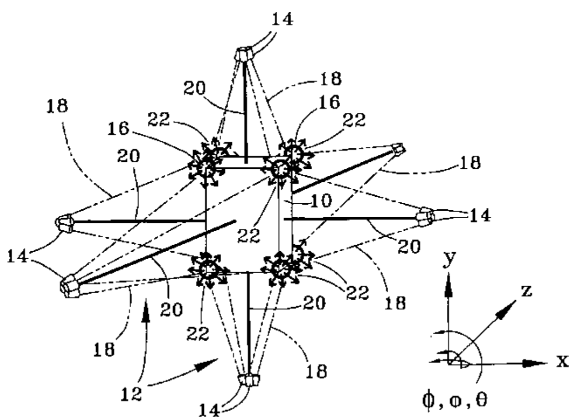


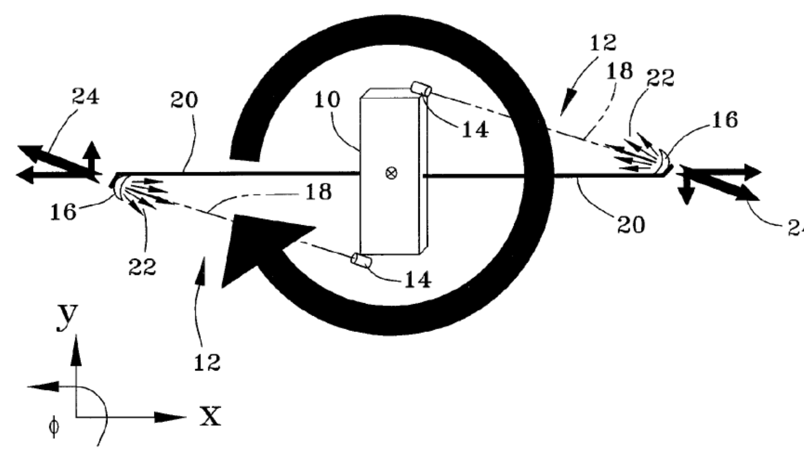
Summary of Solutions – EM Capture

	Capture Ellipses	Skipping Stone	Single Pass	N-pass
Capture Time	Very high	About 1 week	72 hours	Varies
Payload Mass per Time	Low, few solenoids	Very high, many packages	Moderate	Varies, from moderate to low
# Solenoids	Lowest	Extremely large	Moderate	Varies, from moderate to low
Launch Window	Small even with turning	Always open	Small even with turning	Small even with turning
Total Energy	Low, not much to keep up	Huge, many solenoids	Moderate, quite a few solenoids	Varies, from moderate to low
Cost	Cheapest solution available	Very expensive	Moderately high	Varies from moderate to low

Ablation Station Keeping

- Orbital operations require thrust and station-keeping.
- To avoid the need for chemical propellants, use slag ablation.
- Shuttered lasers (or e-beams) on slag generate reaction force.
- Suitable configuration allows 6 degree of freedom movement.
- Payload canisters to GSO would include:
  - Silicon solar panels
  - Aluminum wiring and structural materials
  - Formed slag for ablation targets

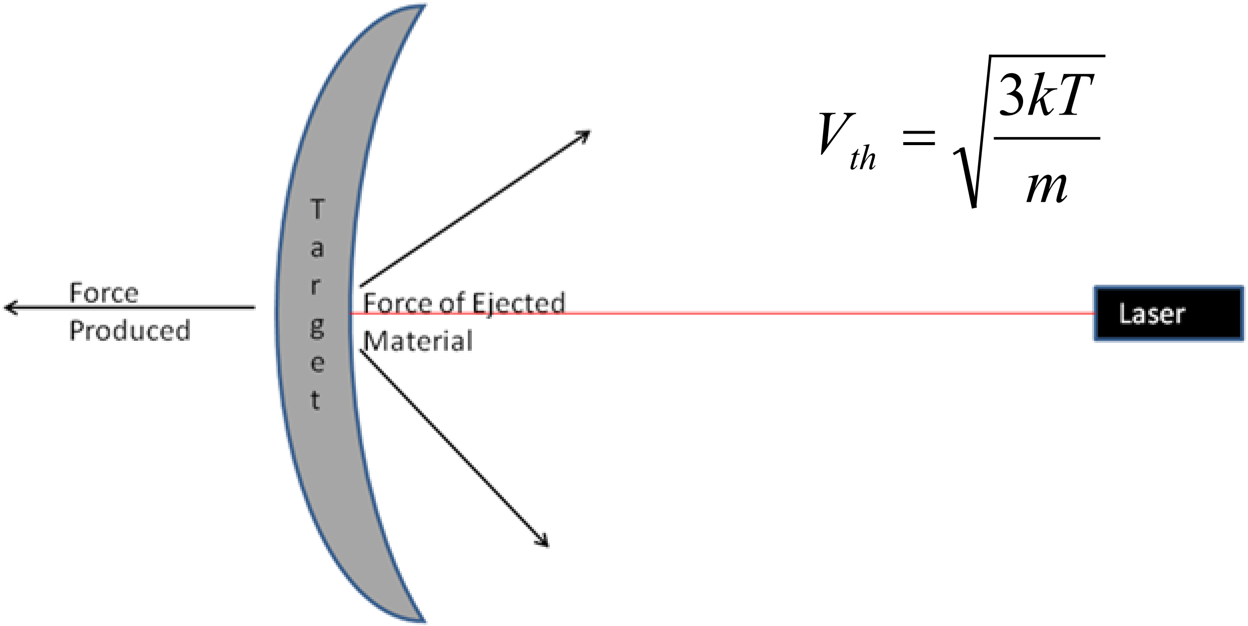




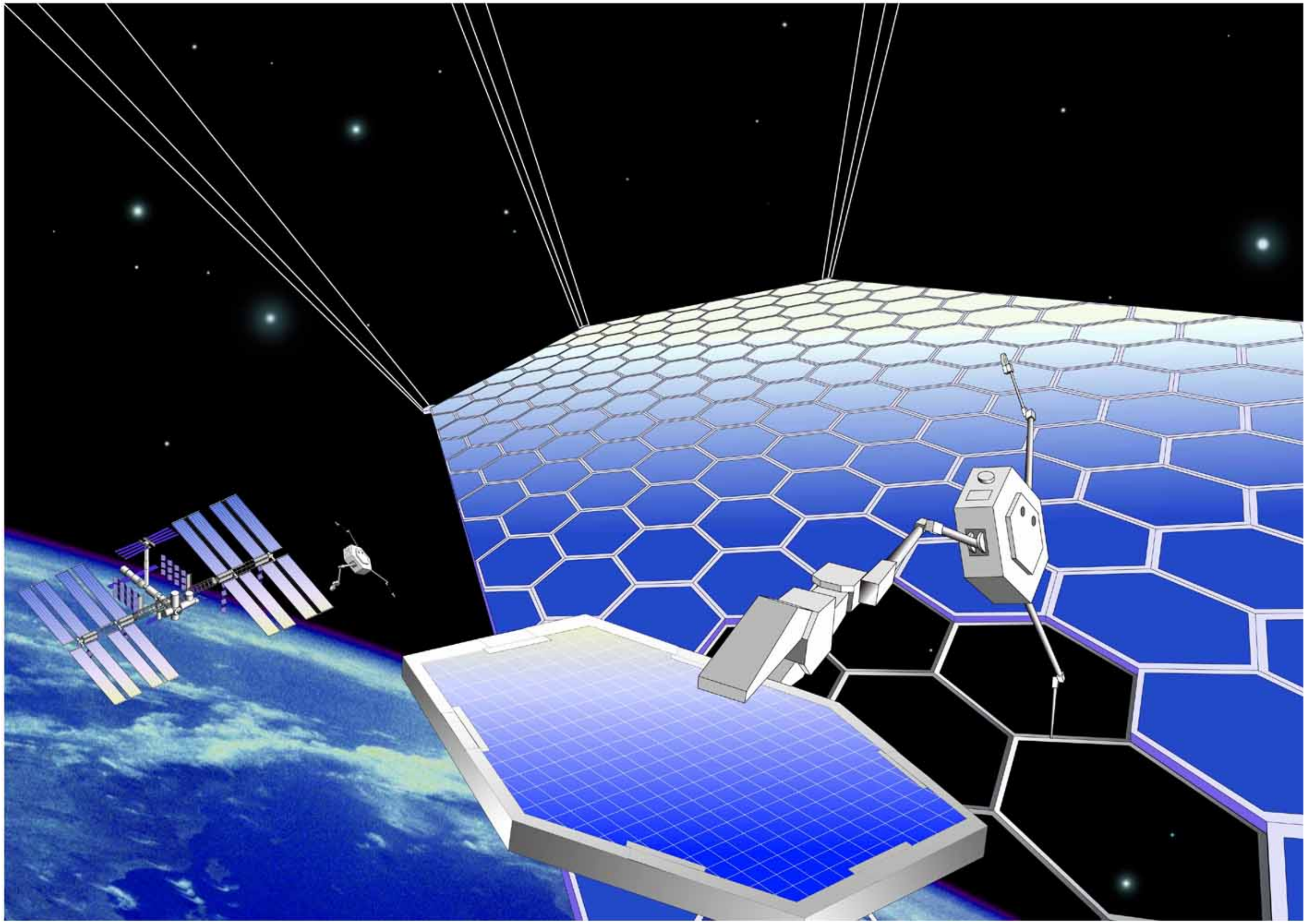
Ablation Station Keeping Slag from Isotope Separator

- 20 W laser, spot size = 1 mm
- Vaporize at temperature = 4000 °K
- Sum vertical components of velocity

$$V_{th} = \sqrt{\frac{3kT}{m}}$$



On-orbit Construction by Robot




launch seen from ISS

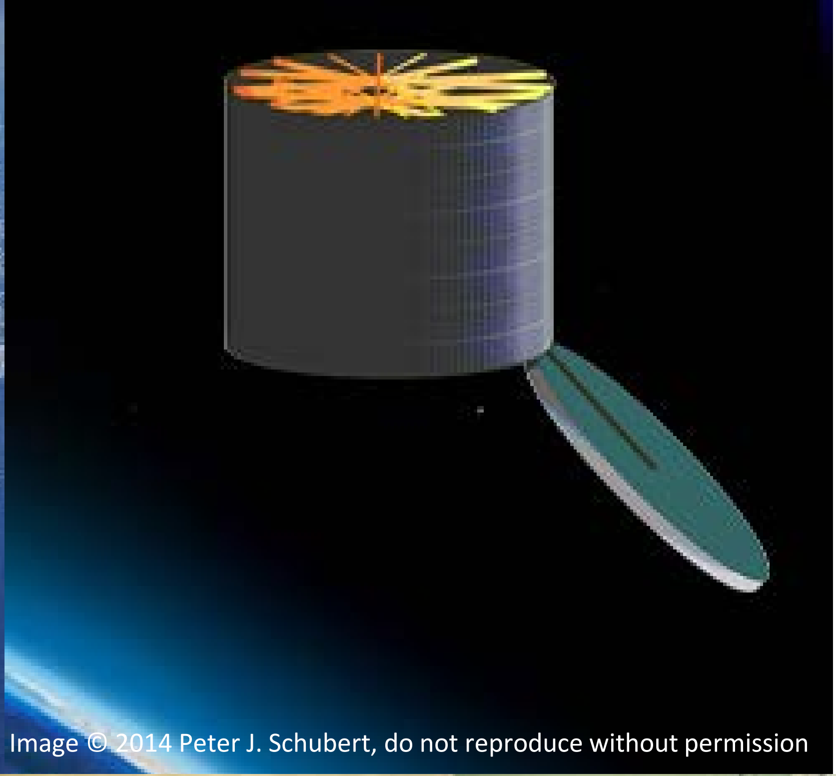
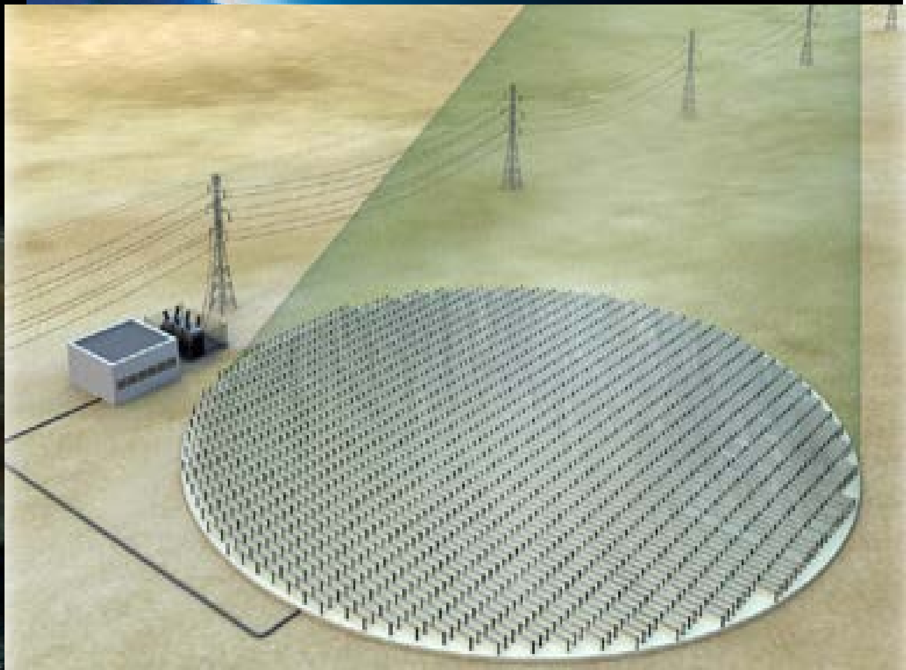


Image © 2014 Peter J. Schubert, do not reproduce without permission


railgun launcher



Scale-up

PAPERS

"Energy and Mass Balance for a Cislunar Architecture supporting SSP," Schubert, AIAA SPACE 09, 14-17 Sept 2009, Pasadena, CA

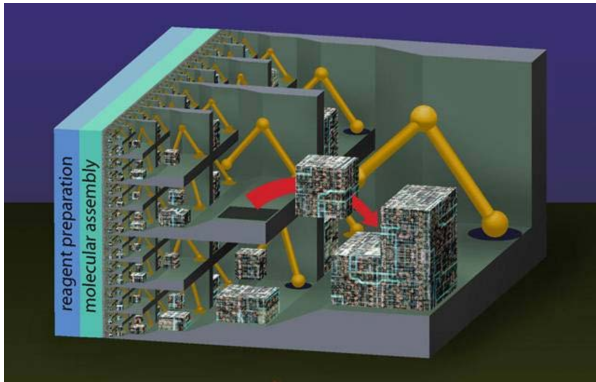
"Bootstrapping Space-based Manufacturing from a Deep Gravity Well," Card, Schubert Intl Space Development Conf, 28-31 May 2009, Orlando, FL

29 April 2009

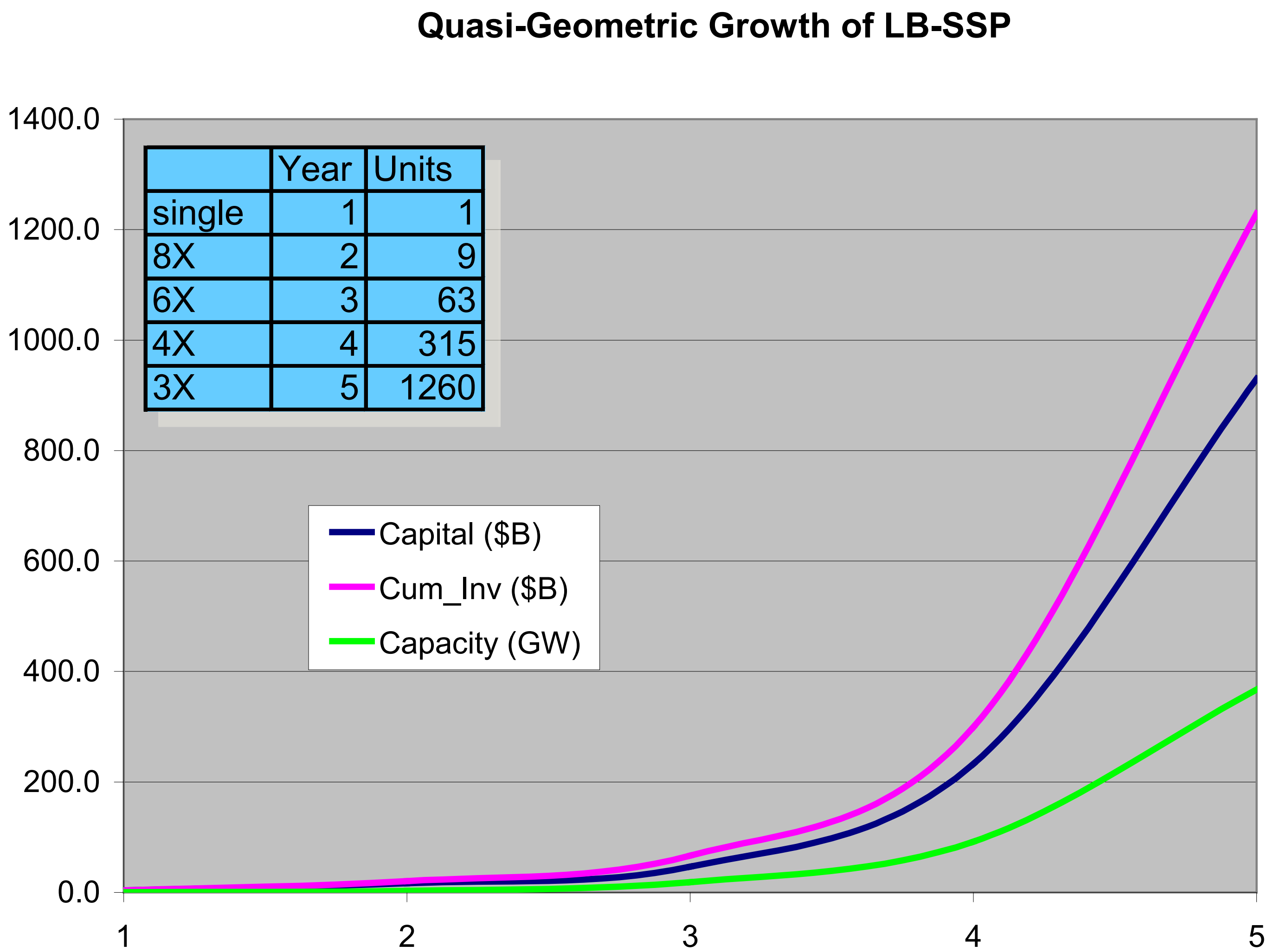
"Synergistic Construction Mechanisms for Habitats in Space Environs," Schubert, International Space Development Conference 2006, Los Angeles, CA 2006

Geometric Manufacturing

- No known power source can meet projected energy needs in time!
- New power sources must scale GEOMETRICALLY.
- Lunar factories which are partly self-replicating may be the only viable long-term energy solution.

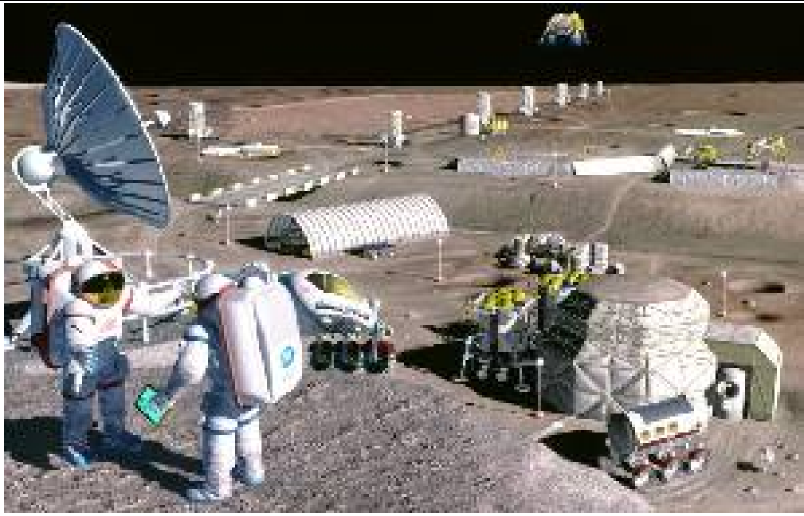


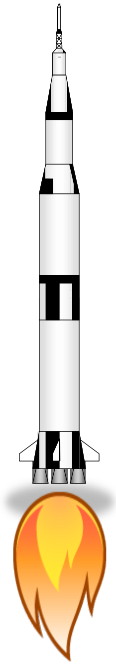
Scale-up of Lunar-based SSP



	Year	Units
single	1	1
8X	2	9
6X	3	63
4X	4	315
3X	5	1260

Mass Totals
Tin Can SPS
Lunar ISRU
Cislunar Transport



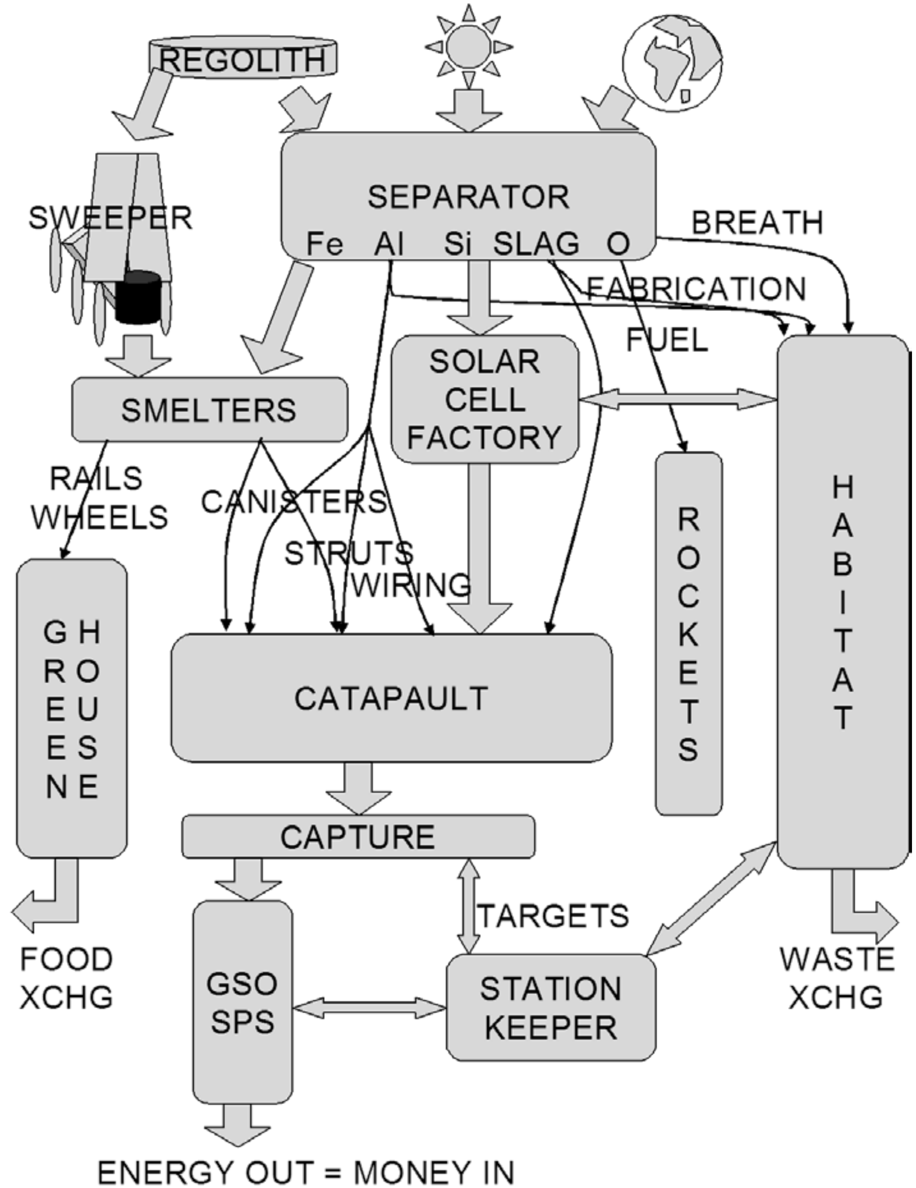


Architecture - mass	
Earth-to-moon (kg)	7.53E+05
Earth-to-GEO (kg)	2.02E+07
lunar-made (kg)	6.29E+05
Earth-made (kg)	1.93E+09

- *Most mass is concrete footers of rectenna*

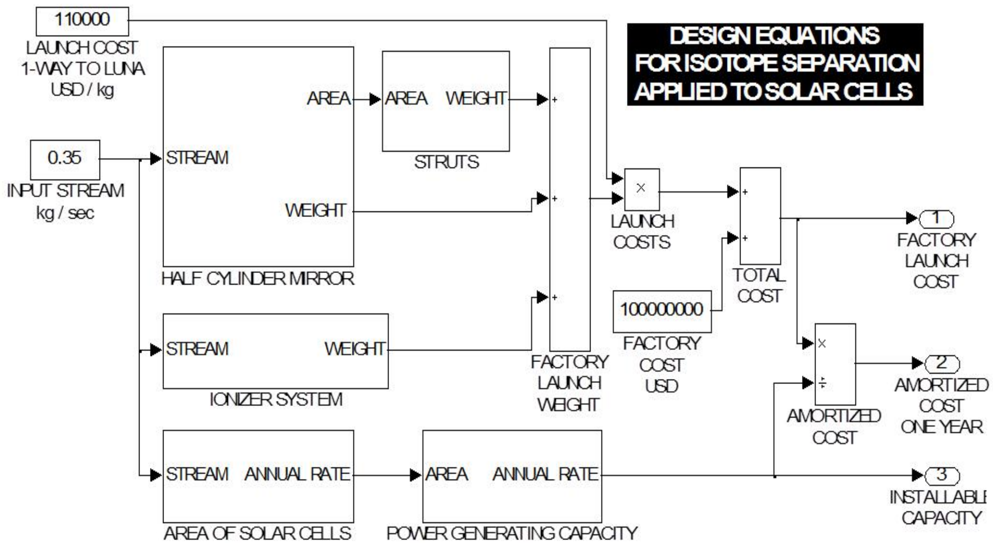
Self-sustaining Cislunar Architecture

- Sell baseline power to Earth.
  - Costs at 5 years = 0.16 USD/kWh
  - Eases demand for petroleum
  - Reduces CO_2 emissions
  - Perpetual, green energy source!
- Use “geometric manufacturing” to produce more factory capability on Luna and reduce costs even further.
- Invest revenues in infrastructure to build factories, resort hotels, ship-building, fuel and food.
- Create a self-sustaining cislunar economy providing benefit back to the Earth.

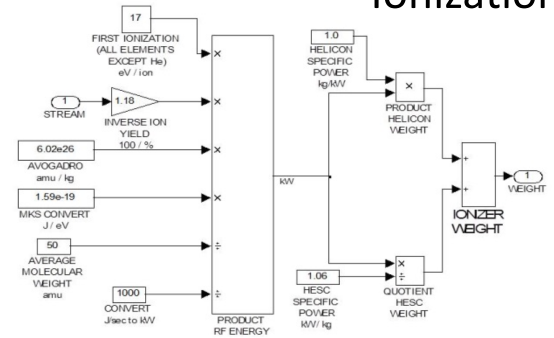


DESIGN EQUATIONS FOR ISOTOPE SEPARATION APPLIED TO SOLAR CELLS

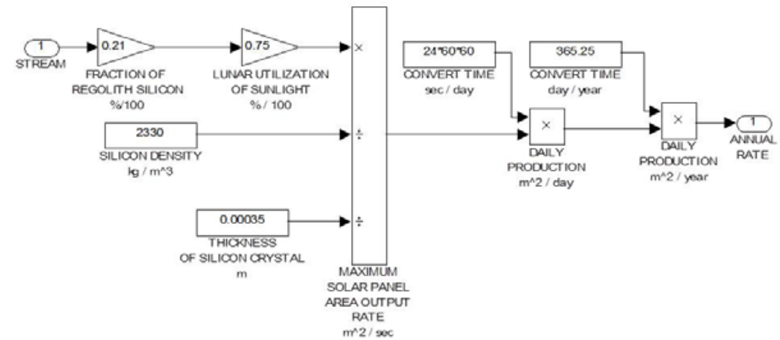
Factory System



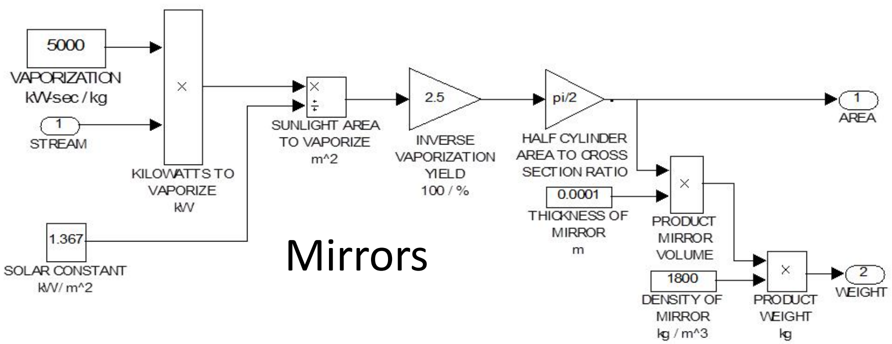
Ionization



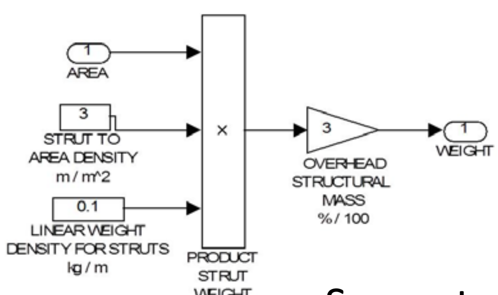
PV Panel Production



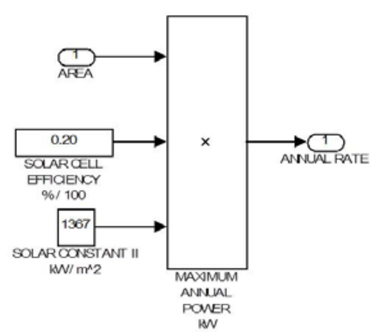
Mirrors

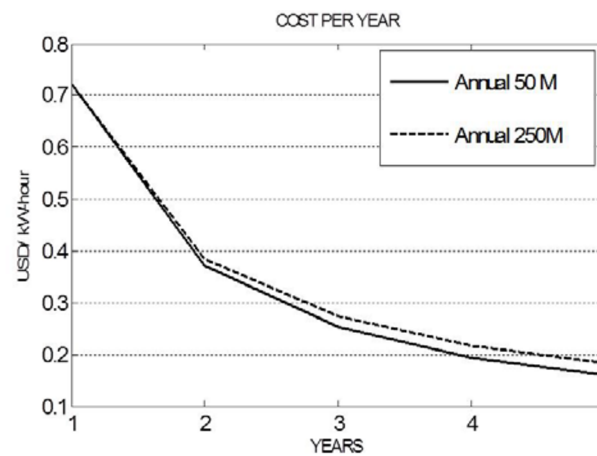


Superstructure



Factory Capacity





Payoff

Average US Price for Electricity = 0.10 USD/kWh

Hours in a year = 8766

SPS with 5 GW delivered <u>revenue</u> = 4.8 B USD/yr

For optimistic launch costs,
<u>capital</u> + <u>expense</u> totals for SPS #1 = $28 B USD

Simple payback SPS #1: 6 years

SPS #2 payback: < 1 year

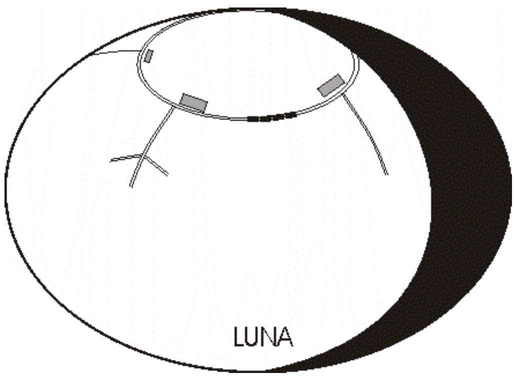
“Tin Can” SPS

THANK YOU

Peter J. Schubert

Circumpolar Lunar Railroad

- Lunar libration (nodding motion) is 6° degrees.
- A permanently sunny location is very unlikely.
- Therefore, to get 100% sunlight, need a rail around the lunar poles*
- Twin rails must be at least 1260 km
  - Use fibrous basalt or formed slag for cross-ties
- A light rail at 40 cm^2 cross section (total) requires 28 kg/m of Fe
  - With Free Iron Sweeper, needs a swath 10 meters on each side
- Takes 2.5 years to complete (best case)
  - Assumes 2 or 3 manufactories – so 1 is in sunlight at all times
  - Ignores contours, which add to linear length
- Circumpolar railroad enables:
  - Continuous factory operations
  - Agriculture & waste recycling
  - Transportation system capable of reaching valuable ore bodies



** Assumes nuclear reactors will be unpopular with taxpayers and other space-faring nations*

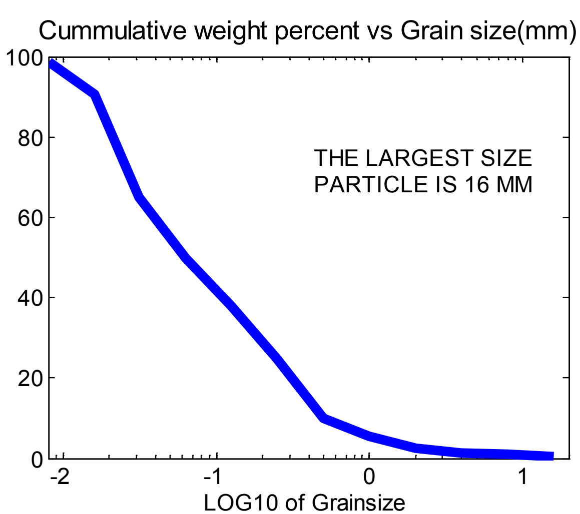
Free Iron Sweeper

- **Metallic iron is 0.1-0.5% of lunar regolith (assume 0.3%)**
- **Superconductors carry 10 A/cm^2 @ 800 m length**
- **Assume magnetization of 150 (very conservative)**
- **Coil field must produce magnetic force sufficient to:**
  - Lift the iron particle
  - Hoist the column of material above the particle
- **Regolith assumed 50 cm deep and 37% porous**

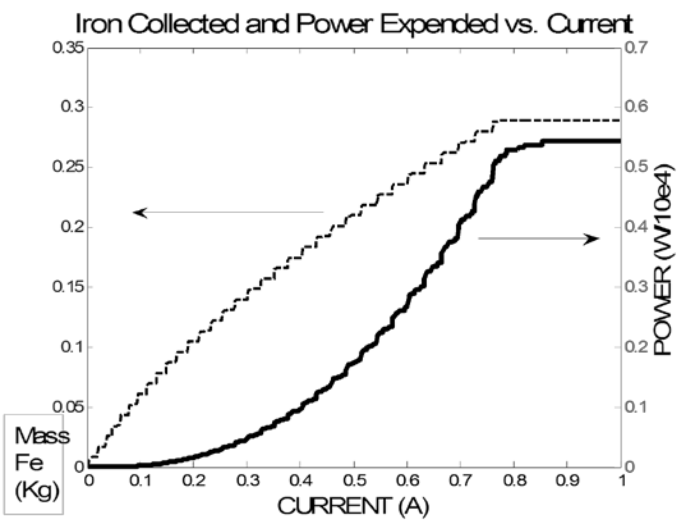
$$Br_{FAR} = \frac{1}{4}\mu_0 NI\cos(\theta)$$

$$m_P = B\chi\mu\pi(\frac{d}{2})^2$$

$$F = \frac{M \cdot m_P}{\mu \cdot r^2}$$



- **Time-of-flight worst case 0.9 seconds per 200 cm^2 cross-section**
- **5.5 kW continuous power needed**
  - 4x4 m solar array
- **0.3 kg/sec max extraction rate.**



Habitat Construction Methods

- Isotope separation yield assumptions
  - Vaporization yield for low-gravity, pulsed configuration = 33%
  - Ionization yield = 85%
  - Suggests that 72% of throughput is slag
- Un-separated materials will be hot and refractory
  - Use waste heat in a Sterling cycle
  - With movable workpiece, can form additive shapes (bricks)
- Trim bricks with lasers, wire saws, or plasma polishing.
- Welds via capillary action of molten aluminum
  - Wicks into interstices
  - Alloys with refractory slag material
  - May form an airtight seal
- Interlocking shapes assembled into a rotating shell for artificial gravity in orbital habitats.